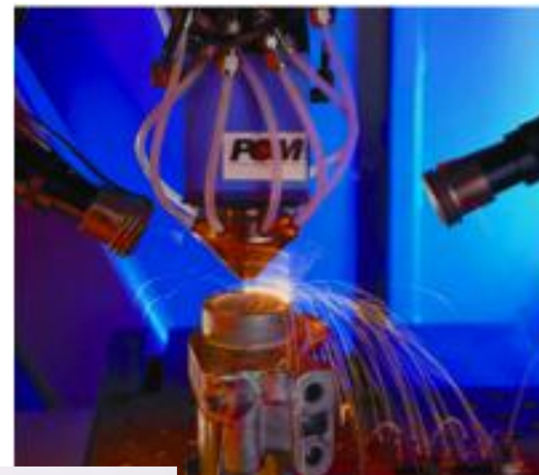
Direct Manufacturing at ORNL

- Revolutionary manufacturing technologies in which feed material is added at specific locations to build net-shaped components from computer models
- Numerous benefits over conventional processing techniques
  - Decrease Energy and Waste
  - Component Design Optimization
  - Create "Geometrically Impossible Designs"
  - Resurrect US Manufacturing
  - Diversified Manufacturing
  - Decreased Lead Times

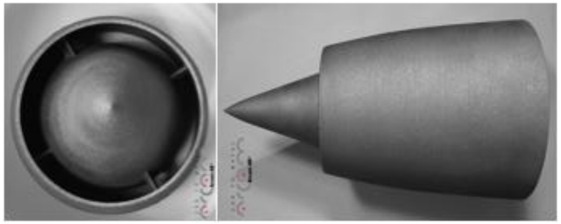


Direct Manufacturing at ORNL

- The Direct Manufacturing capabilities at ORNL encompasses a broad scope of direct manufacturing technologies including:
    - Electron Beam Deposition (Slide 3)
    - Laser Deposition (Slide 7)
    - Ultrasonic Additive Manufacturing (Slide 10)
    - Gel Casting
    - Plasma Arc Lamp & IR Technologies
    - Polymer 3D Printing of Small Components

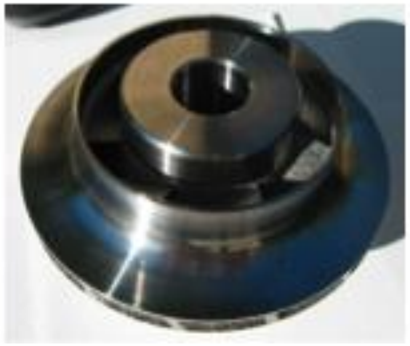
Electron Beam Deposition:

- Electron beam used to melt a powder bed under vacuum
- Excellent compositional control with microstructural refinement showing increased mechanical properties
- Precise control of complex geometries
- Many applications including Aerospace, Automotive, Biomedical



Gas Turbine Engine Compressor Support Case

Rocket Engine Impeller

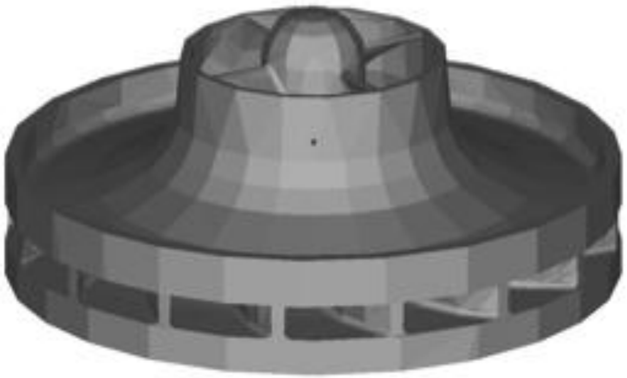


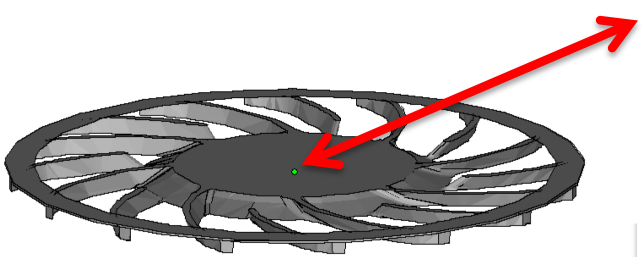
Engine Part with Lattice Structure

Customized Trabecular CMF Implant

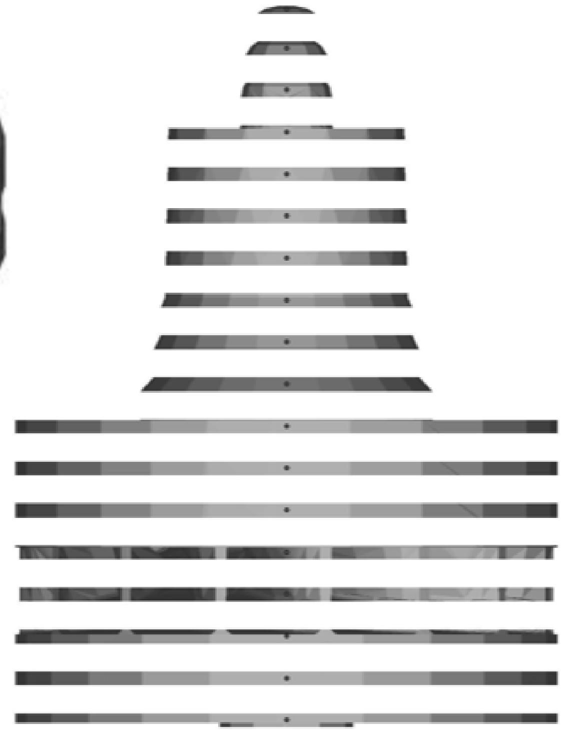
How Arcam Works: Computer Design

Design the Part

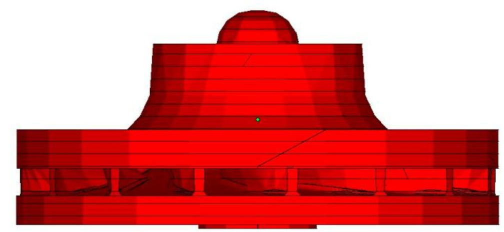




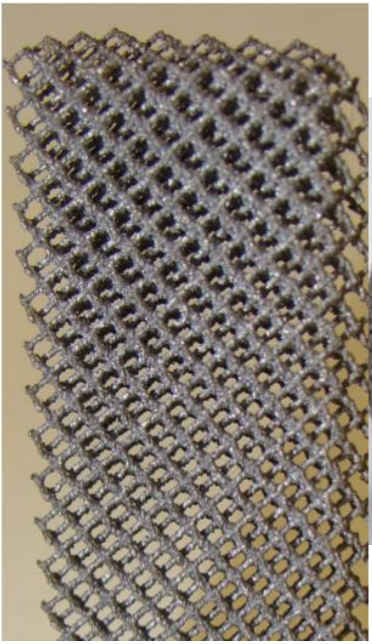
Slice Part into Layers

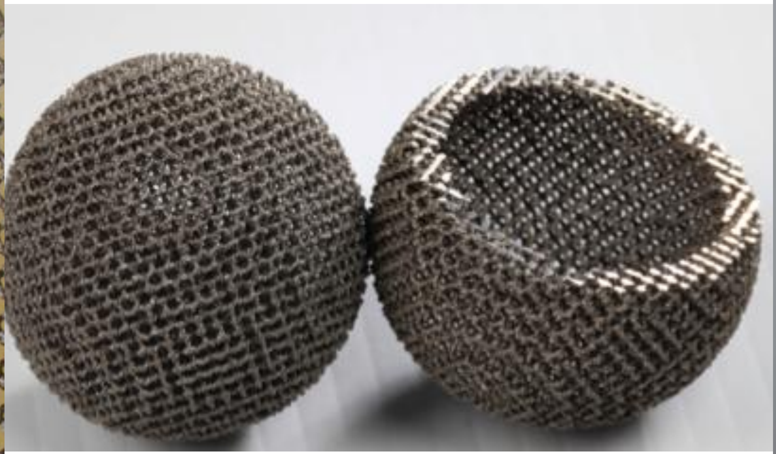


Deposit Individual Layers



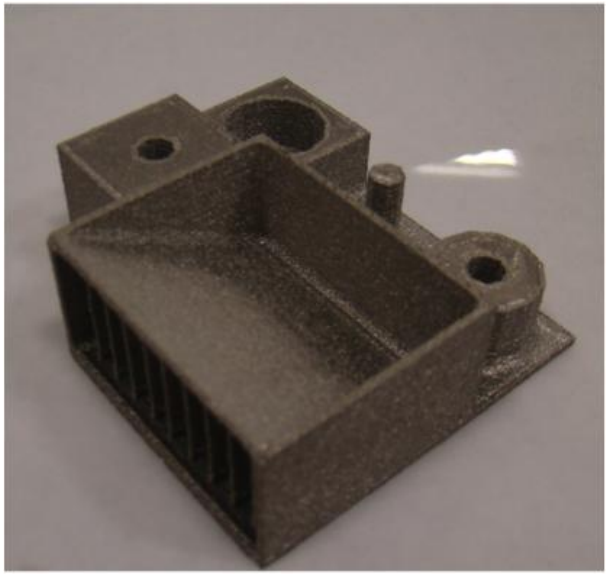
Electron Beam Melting



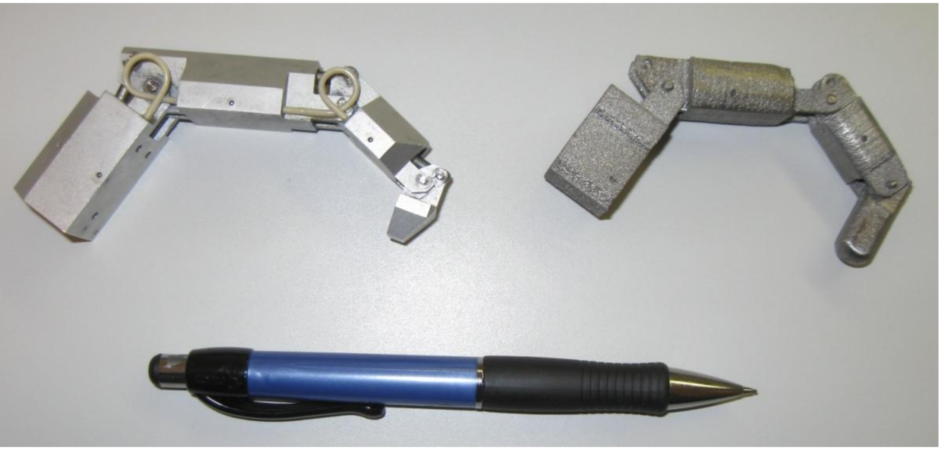


Current Research:

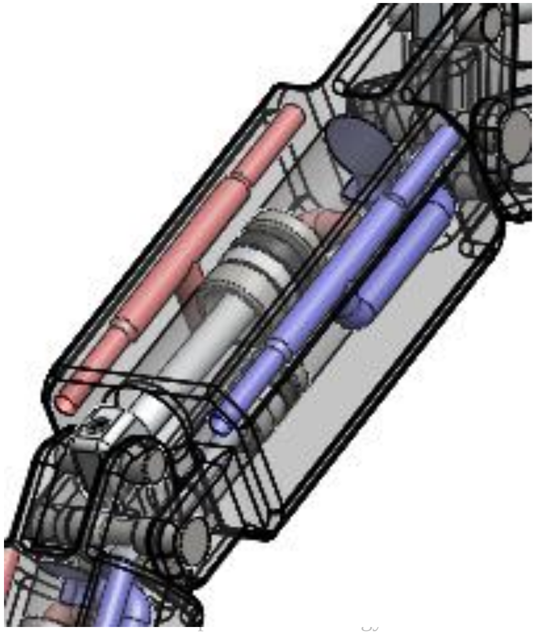
- **Build of Parts Impossible or Near to Impossible to Build**
- **Implementation of Low-Cost Ti feedstock materials**
  - **10X decrease in material cost**
  - **HDH CP Ti: Grade 3,4 Strength, Grade 1,2 Elongation**
- **Development of new Alloy Systems**
  - **Machineable TiAl: EBM can improve existing alloys**

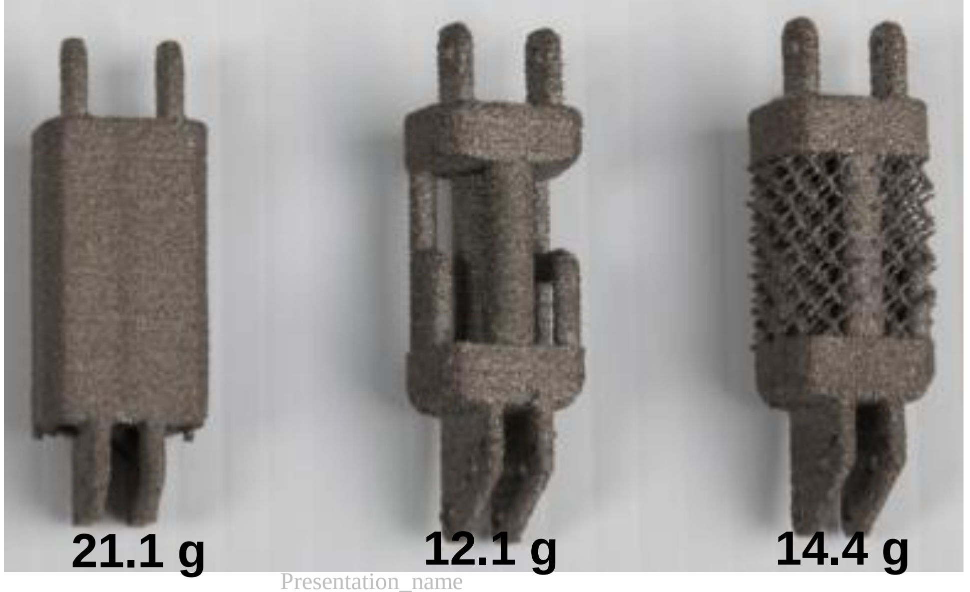


Direct Manufacturing Utilizing New and Conventional Titanium Powders



- Graded Materials, Composites, and Improved Structures for Enhanced Performance
- Advanced Robotics
  - Aluminum finger (65 grams, $6500 to fabricate)
  - Titanium finger (61 grams, $20 worth of material)
- Advanced Design Structures
- Fast Design Iteration

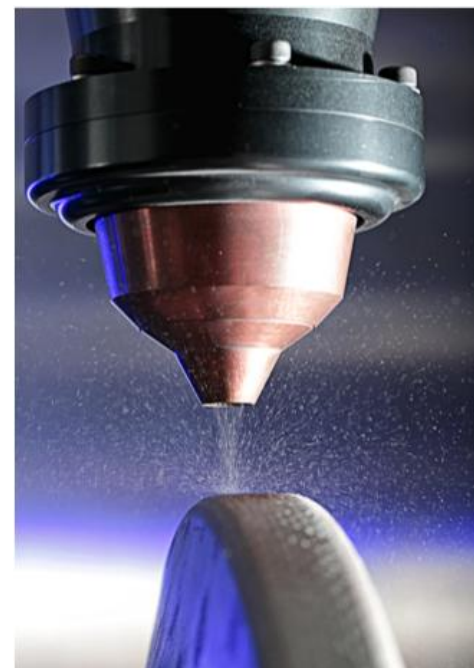




Laser Metal Deposition

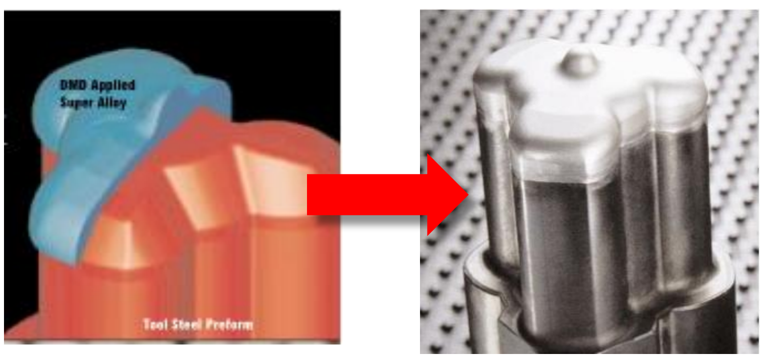
Precision Optical Manufacturing

- Laser Beam melting of a continuously fed powder stream
- Site specific compositional control for production of functionally graded components with optimized properties
- Ability to add material to large parts including turbine blade repairs, surface treatments of dies, punches, and bits for increased wear ability and thermal behavior



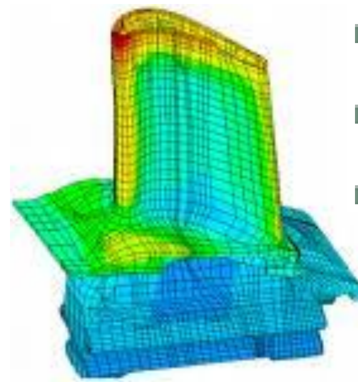
Laser Metal Deposition

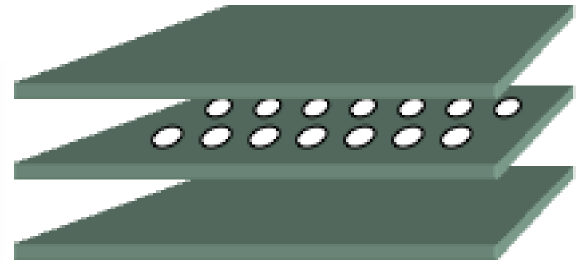
- Computer controlled 5-axis motion
- Inert chamber for reactive materials
- Closed Loop feedback system for precision deposition
- 2 powder hoppers allow for Multi-material Deposition:



Laser Deposition, Composites for Application

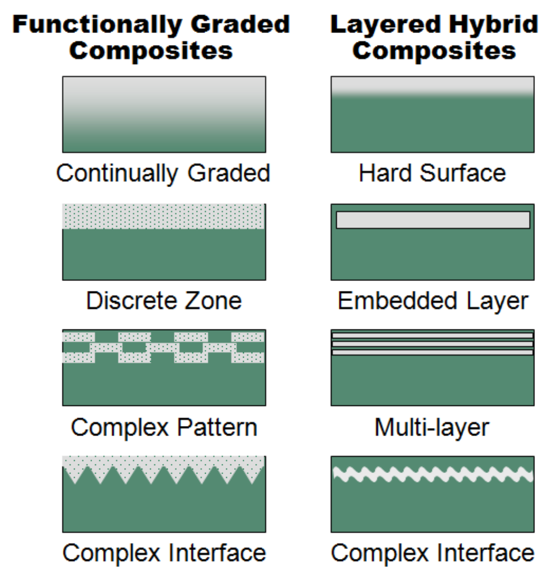
- Graded Materials
- Coatings or Rebuilds
- Powder Metallurgy Versus Additive Manufacturing

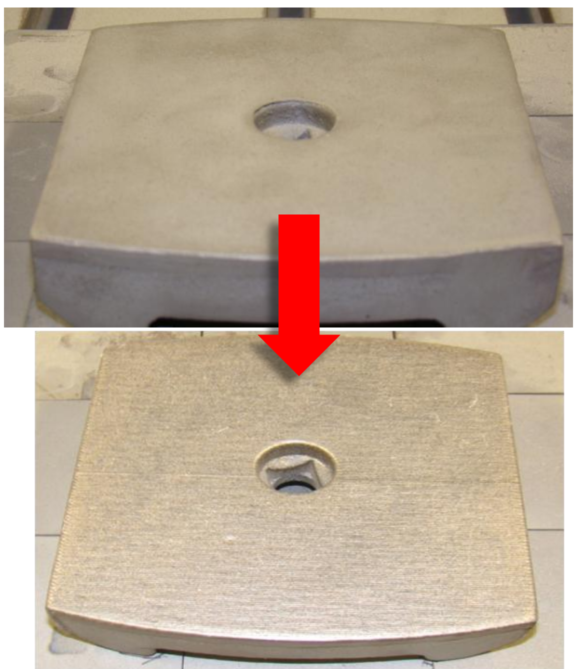




Embedded Particle Arrays

Graded Compositions



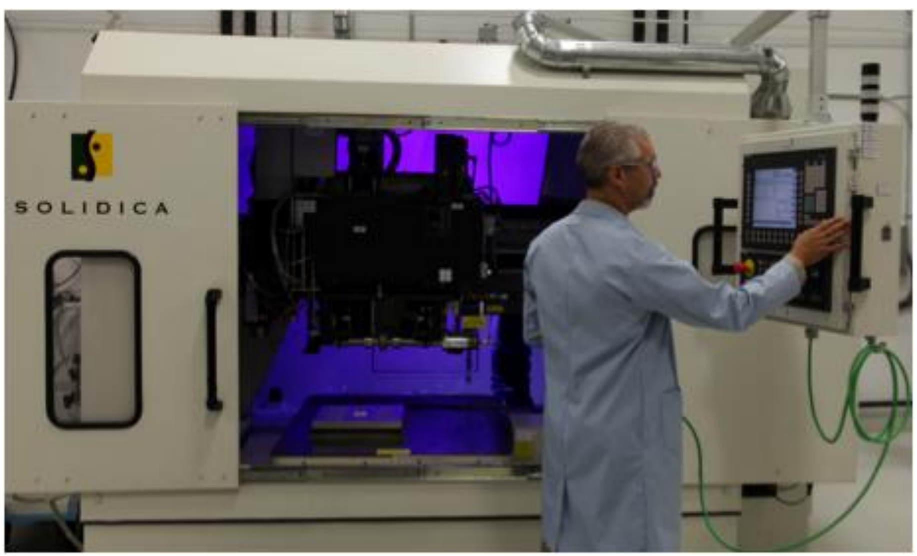


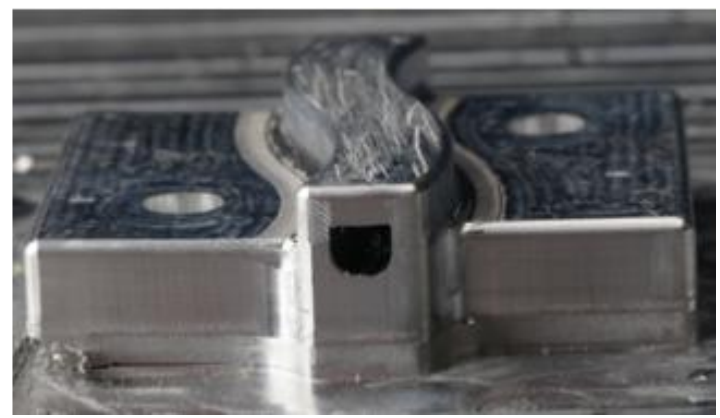
Coating of Components

Laser Deposition of Reactive Materials

Ultrasonic Additive Manufacturing

- Ultrasonic Energy is used to bond thin tapes or sheets of material into 3-dimensional components
- Combination of additive and subtractive techniques allows precise machining of components with complex geometries and intricate internal channels
- Low temperature processing allows the ability to incorporate sensitive materials such as fiber optics for sensors





Advantages of a Ultrasonic Additive-Subtractive Deposition

- Temperature Sensitive Materials
- Absent liquid-solid transformations
- Fast
- Lower energy consumption – eco friendly
- Improved dimensional accuracy
- No atmosphere control requirements
- Well suited for joining of dissimilar metals

Ultrasonic Consolidation (Additive)

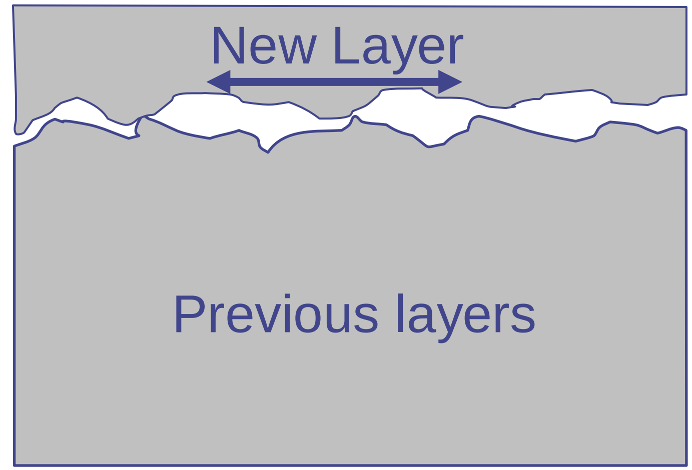
Ultrasonic energy transferred to
material

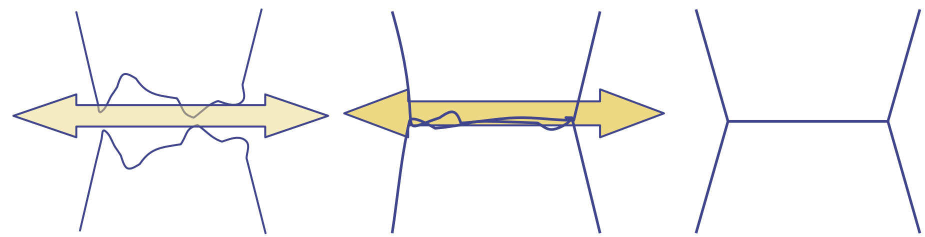
Bond Stages

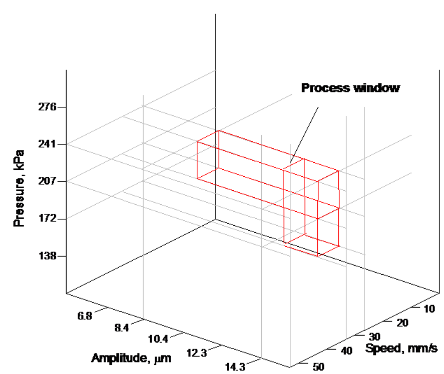
- Asperity collapse
- Partial oxide disruption
- Localized softening and adhesion

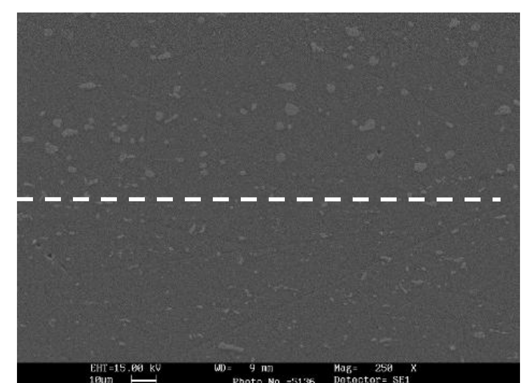
Key Parameters

- Amplitude (15μm)
- Sonotrode force (500N)
- Rolling speed (3cm/s)
- Sonotrode texture
- Frequency (20 kHz)
- Power (3 kW)



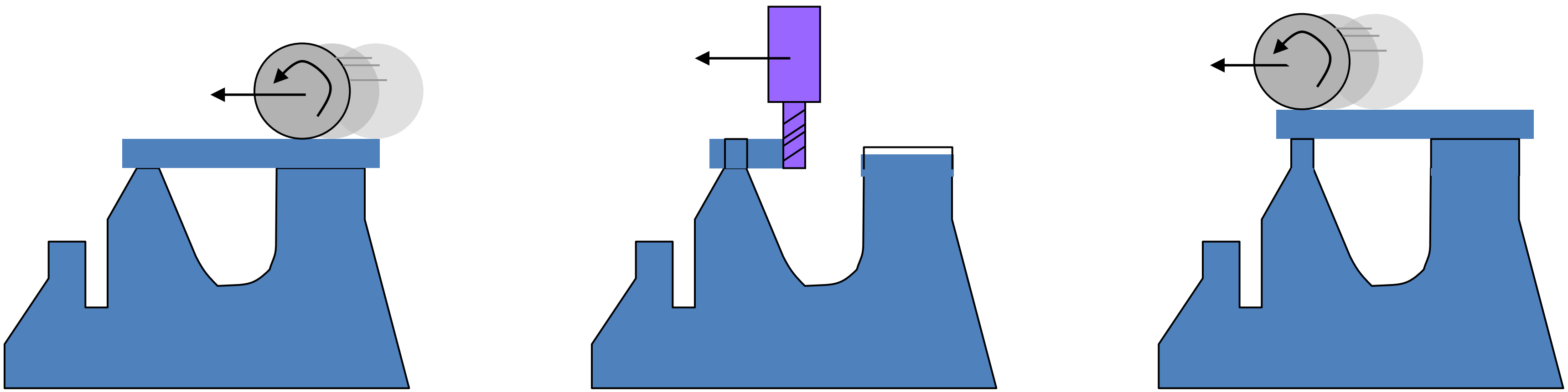






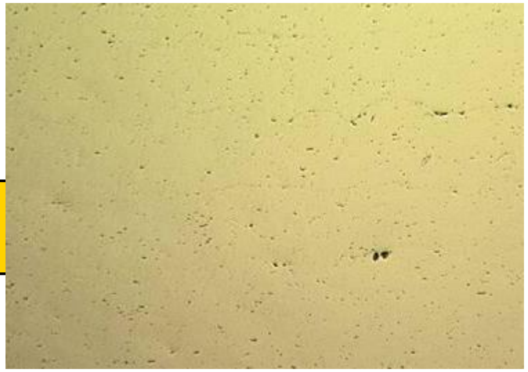
Ultrasonic Consolidation (Subtractive)

<u>Ultrasonic Consolidation</u> = Solid State Deposition + CNC Subtraction

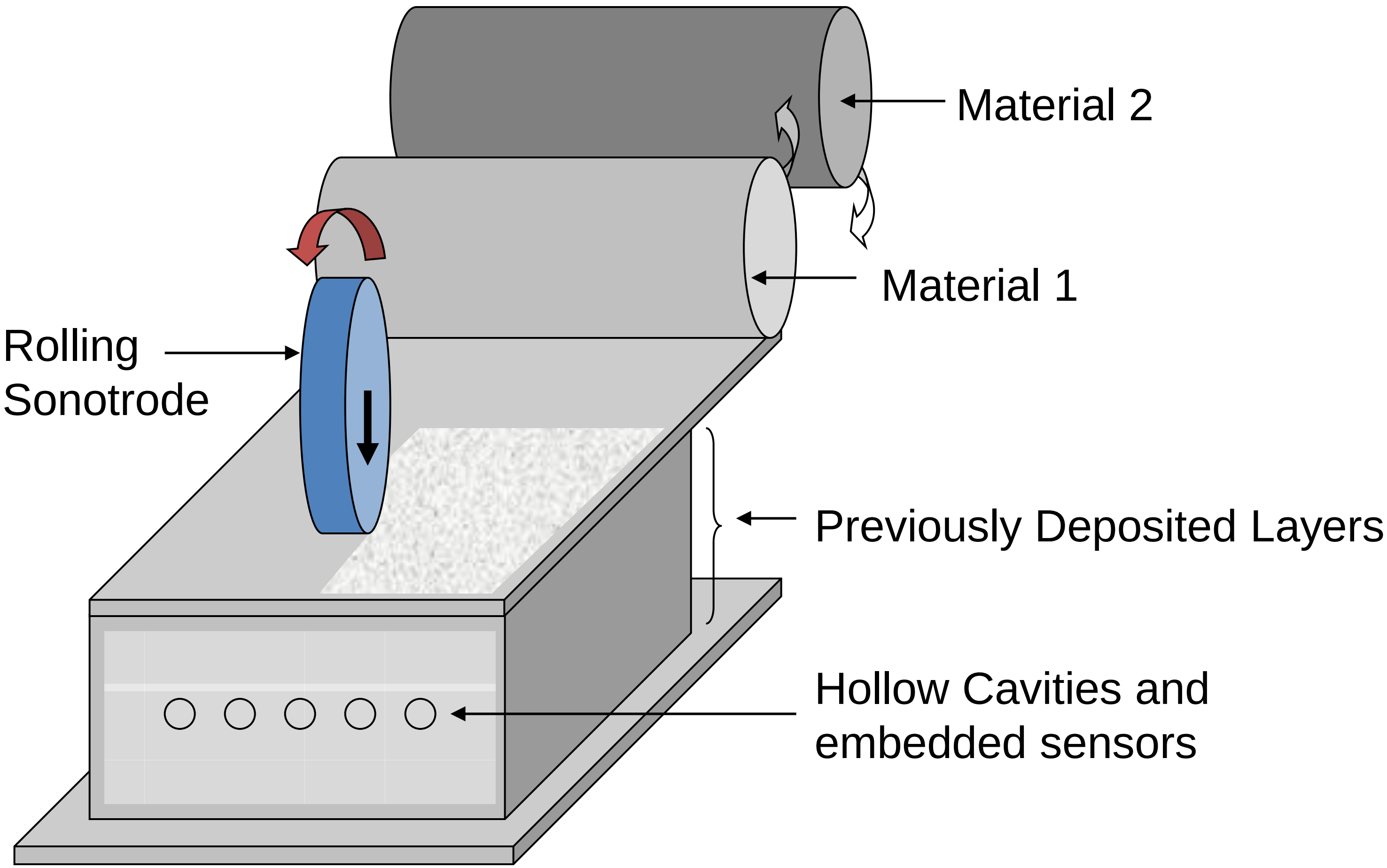


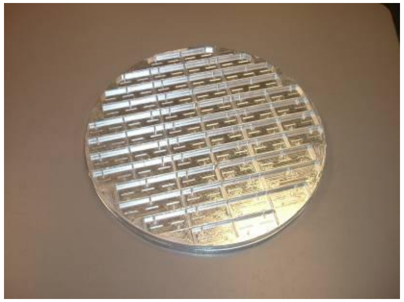
UC Deposition → CNC Removal → UC Deposition …

True metallurgical bond
8 layers Al, 100x



Advanced Materials via Solid State or Ultrasonic Additive Manufacturing





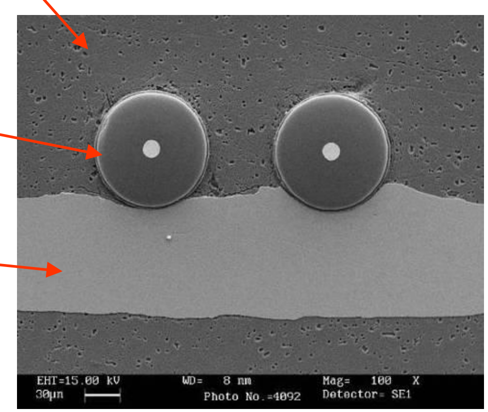
Dissimilar UC Matrix Potential

	Al	Be	Cu	Ge	Au	Fe	Mg	Mo	Ni	Pd	Pt	Si	Ag	Ta	Sn	Ti	W	Zr
Al Alloys	● (UC)	●	● (UC)	●	● (UC)	● (UC)	●	●	● (UC)	●	●	●	● (UC)	●	●	● (UC)	●	●
Be Alloys		●	●			●										●		
Cu Alloys			● (UC)		●	●	●	●	●	●	●		● (UC)	●		●	●	●
Ge					●						●							
Au					●	●			●	●	●	●	●			●	●	●
Fe Alloys						● (UC)			●	●	●		●	●		●	●	●
Mg Alloys							●						●			●		
Mo alloys								●	●		●			●		●	●	●
Ni Alloys									● (UC)	●	●			●		● (UC)	●	
Pd										●			●	●				
Pt Alloys											●	●		●		●	●	
Si													●	●				
Ag Alloys													●	●				●
Ta Alloys														● (UC)		●	●	
Sn															●			
Ti Alloys																●	●	
W Alloys																	●	
Zr Alloys																		●

● Material pair proven for ultrasonic welding

(UC) Material pair tested for UC

- Process well suited to dissimilar metals and multi-material laminate
  - No liquid phase metallurgical incompatibilities
- Multiple metal foils can be combined
- Fiberoptic, B and SiC fibers can be embedded without deleterious reactions with Al matrix



UC Part Examples